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14. ABSTRACT
This research project focused in three areas. The first area developed fault detection and location schemes for ungrounded and high resistance grounded power systems. An evaluation of the impacts of different grounded schemes on system protection and power quality was conducted. The second area concentrated on developing schemes to isolate sensitive loads from voltage sags caused by faults and pulsed loads. One project developed a fault current limiter based on a vector-switching. A second implemented a static series compensator with a flywheel energy storage system to connect between sensitive loads and the system. The third developed an interface for pulsed loads combined with local energy storage. The third area of this project developed an analog model power system for testing protection schemes and power electronic converters.

15. SUBJECT TERMS
Power Systems Protection and Relaying, Power Quality, Voltage Sag Mitigation, Model Power System

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FINAL REPORT

GRANT #: N00014-00-1-0477

PRINCIPAL INVESTIGATOR: Brian K. Johnson

CO-PRINCIPAL INVESTIGATOR: Herbert L. Hess

INSTITUTION: University of Idaho

GRANT TITLE: Protection and Reconfiguration of Zonal Distribution Systems

AWARD PERIOD: 1 March 2000 through 31 March 2003

OBJECTIVE: Principal objectives of this research were: 1) Develop methods for rapid, secure detection of faults on power distribution systems, 2) Identify methods to maintain the quality of power supplied to loads during faults, and 3) Develop a laboratory test setup to verify protection and voltage sag mitigation schemes.

APPROACH: The tasks were divided into three areas:

1. Several groups of students (mostly through undergraduate senior design projects) concentrated on modifying and improving the analog model power system (AMPS) (donated by Idaho Power System and Schweitzer Engineering Laboratories) for use with this project.
2. Three graduate students explored different approaches for limiting the impact of voltage sags due to faults or pulsed loads on the rest of the loads in a tightly coupled electric system.
3. Another graduate student performed a study of the impacts of different grounding schemes (i.e. ungrounded, high resistance grounded, etc.) on system protection and power quality. The same student also developed schemes for identifying and locating faults on ungrounded or high resistance grounded systems. Another student developed arcing fault models (largely funded by another ONR project).

ACCOMPLISHMENTS: The list below is based on the three areas from the approach described above.

1. Analog model power system (AMPS):

- Developed a data capture system to collect voltage and current data from experiments on the system with high speed sampling of line voltages and currents and a graphical display. Data can be exported for postprocessing.
- Commercial protective relays from Schweitzer Engineering Laboratories connected to the system. Protection schemes with and without communication between relays implemented.
- Developed a fault initiator allowing phase-to-ground, phase-to-phase, double-phase-to-ground, or three-phase faults to be initiated simultaneously at 3 separate locations in the system (with +/- 0.5 degrees point on voltage wave accuracy). The faults can evolve over

time (i.e. from phase-to-ground to double-phase-to-ground. A method to create a variable impedance fault was developed for use with the fault initiator.

- Programmable solid-state circuit breakers were developed for use with system. The breakers can be programmed to imitate circuit breakers with clearing times ranging from a fraction of a cycle to 6 cycles. Will respond to trip commands from commercial or prototype relays.

- Detailed model of AMPS and relays developed in alternate transients program (ATP).

- Scheme for secure remote access to the AMPS over the Internet developed (with lab technicians present in the lab to ensure safety of the system). Remote users can set the protective relays, program the fault initiator and system controls, conduct a study, and transfer event data back to their own computer for post-processing.

2. Approaches for limiting the impact of voltage sags on a tightly coupled electric system.

- Developed a scheme for isolating large pulsed loads from the distribution system so the pulsed operation doesn't cause voltage sags for other loads. The pulsed load is interfaced to the ac system through an intermediate dc bus that has local energy storage. A variable impedance or converter controls on the ac interface added to improve isolation.

- A variation on the dynamic voltage restorer (DVR) installed on terrestrial power systems was developed. It consists of a voltage source converter connected in series with the distribution line to inject voltage to compensate for voltage sags elsewhere on the system. This scheme utilizes a flywheel energy storage system to allow compensation of deeper or longer lasting voltage sags (or sequential sags). Simulation models in PSCAD/EMTDC.

- Development of a fault current limiter based on a vector switching ac/ac converter. The converter acts as a variable ratio transformer to inject controlled impedance into the system. The fault current limiter reduces fault current levels to reduce depth of voltage sags and reduces fault duty of circuit breakers. It must be coordinated with protection scheme.

3. Protection scheme development:

- A study of the impacts of different grounding schemes (i.e. ungrounded, high resistance grounded, resonant grounded, low impedance grounded and solidly grounded) on system protection and power quality. Study documented experiences in several industries that have moved from ungrounded to high resistance grounded systems to improve system performance and reliability. The chief gains are (1) improved protection response, (2) elimination of capacitive voltage magnification due to sputtering faults (there have cases with 480V systems reaching nearly 10kV relative to ground). The chief drawback is the added cost/weight of grounding resistor (and possible transformer).

- Evaluation of schemes for identifying single-phase-to-ground faults on ungrounded and high resistance grounded systems in terms of speed

and security. Development of a single-ended and communication-aided schemes for locating single-phase-to-ground faults on ungrounded and high resistance grounded systems. Fault identification and location schemes simulated using PSCAD/EMTDC and tested using AMPS.

- Stochastic arcing fault models were developed in ASCL to representing the statistical variation of the arc impedance observed in experimental studies performed at KEMA in Philadelphia.

CONCLUSIONS: The DEPSCoR funding for this project was used to initiate research in several directions related to improving protection and power quality of shipboard power systems. It was also used to build lab infrastructure that can be capitalized on in future projects. Three of the undergraduate students supported through this project were part of the Naval ROTC program and another became an instructor at one of the Naval Nuclear Power training schools. One of the graduate students involved in this work is a member of the Naval Reserve. Project PI's also tried to facilitate contacts between equipment supplies for terrestrial power systems and NAVSEA.

SIGNIFICANCE: The arcing fault model is an improvement over conventional models used in transmission and distribution systems. The fault current limiter and static series compensator with flywheel energy storage are viable for terrestrial or shipboard applications. The fault location scheme for ungrounded and high resistance grounded systems has been viewed positively by engineers at a major relay manufacturer.

PATENT INFORMATION: No patent applications have been filed.

AWARD INFORMATION: Johnson Promoted to Full Professor, Johnson selected as ECE Department Outstanding Researcher, Hess elected to AdComm of IEEE Industrial Electronics Society

PUBLICATIONS AND ABSTRACTS (for total period of this grant):

1. Venkataramanan, G., and B.K. Johnson, "A Superconducting DC Transmission System Based on VSC Transmission Technologies," *IEEE Transactions on Applied Superconductivity*. Vol. 13, No. 2, June 2003, pp. 1922-1925.

2. Balasubramanian, G.K., B.K. Johnson, H.L. Hess, R. Nelson, and D. Flegel, "Design, Modeling and Simulation of an IGBT-Based Solid-State Circuit Breaker," *Proceedings of the 35th North American Power Symposium (NAPS 20003)*. Rolla, Missouri, October 20-21, 2003.

3. Flegel, D.C., R.O. Nelson, R.W. Wall, H.L. Hess, and B.K. Johnson, "An Analog Model Power System for Research and Classroom Use," *Proceedings of the 35th North American Power Symposium (NAPS 20003)*. Rolla, Missouri, October 20-21, 2003.

4. Samineni, S., B.K. Johnson, H.K. Hess, and J.D. Law, "Modeling and Analysis of a Flywheel Energy Storage System with a Power Converter Interface," *Proceedings of the 2003 International Conference on Power Systems Transients (IPST 2003)*. New Orleans, September 28-October 2, 2003.

5. Samineni, S., B.K. Johnson, H.K. Hess, and J.D. Law, "Modeling and Analysis of a Flywheel Energy Storage System for Voltage Sag Correction," *Electric Machines and Drives Conference, 2003. IEMDC'03.* IEEE International, June 1-4, 2003, pp. 1813-1818 (Volume 3).

6. Somani, A., B. Johnson, and H. Hess, "Evaluation and Protection Methods for a Shipboard Power System," *Proceedings of the 34th North American Power Symposium.* October 15-16, 2002, Tempe, Arizona, pp. 288-293.

7. Mangapathirao, M., R. Nelson, R. Wall, and B. Johnson, "Stochastic Approach for Modeling Arcing Faults in Cables From Experimental Data," *Proceedings of the 34th North American Power Symposium.* October 15-16, 2002, Tempe, Arizona, pp. 501-506.

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10. Nelson, R.O., D.C. Flegel, B.K. Johnson, and H.L. Hess, "Undergraduate Research and Teaching Opportunities from a Transient Network Analyzer," *ASEE Annual Conference Proceedings.* June 2002, Session 2322.

11. Gordon, D., K. Hollinger, J. Leman, B.K. Johnson, H.L. Hess, and R.W. Wall, "TNA Fault Controller," *Proceedings of the 33rd North American Power Symposium.* College Station, Texas, October 15-16, 2001.

12. Samineni, S., B.K. Johnson, H.K. Hess, and J.D. Law, "Modeling and Analysis of a Flywheel Energy Storage System for Voltage Sag Correction," Submitted to *IEEE Transactions on Industry Applications.*

13. Mangapathirao, M.V., B.K. Johnson, and G. Venkataramanan, "Fault Current Limiter Using A Series Vector Switching Converter," To be submitted to *IEEE Transactions on Power Delivery.*

14. Mangapathirao, M.V., R.O. Nelson, R.W. Wall, and B.K. Johnson, "Stochastic Approach For Modeling Arcing Faults In Cables From Experimental Data," To be submitted to *IEEE Transactions on Power Delivery.*

15. Somani, A., B.K. Johnson, and H.L. Hess, "Fault Detection and Location for Shipboard Power Systems," To be submitted to *IEEE Transactions on Power Delivery.*

16. Samineni, S., B.K. Johnson, H.L. Hess, and J.D. Law "Isolating Critical Shipboard Loads from Voltage Sags Using a Static Series Compensator with Flywheel Energy Storage," To be submitted to *IEEE Transactions on Power Delivery.*

17. Nelson, R.O., D.C. Flegel, M.C. Staihar, B.K. Johnson, and H.L. Hess, "An Analog Model Power System for Research and Education on the Protection and Control of Special Purpose Power Systems," To be submitted to *IEEE Transactions on Power Systems.*